Grant SPC 99-4026

Studies of Plasma Instability Process Excited by Ground Based High Power HF (Heating) Facilities

FINAL REPORT

The active Heating Experiments (ionospheric modification by ground based high power HF transmitters) were performed in the US, USSR and more recently in Western Europe for over two decades (Utlaut 1970, Utlaut and Cohen 1971, Carlson et al 1972, Gurevich 1978, Stubbe and Kopka 1982). Heating experiments were used to reach understanding of various physical, chemical and plasma processes in ionosphere and to develop a variety of engineering applications (see Gurevich 1978, Migulin and Gurevich 1984, Carlson 1990). Significant results had been obtained but much still remains to be learned. New more powerful Heating Facilities are now under construction by the US Air Force to further push the boundaries of our knowledge of these processes.

It was found that used in modification HF power is sufficient to excite different type of plasma instabilities (Carlson et al 1972, Perkins and Valeo 1974, Vaskov and Gurevich 1975). One of the most significant new physical phenomena, discovered during ionospheric modification was the resonance instability leading to the generation of small scale striations which are plasma density depletions strongly elongated along the Earth's magnetic field (Utlaut 1970, Gurevich 1978). Recently such striations were also observed in Arecibo experiments *in situ* on board rockets (Kelley et al 1995). They have been seen as essentially local stationary depletions of plasma density $|\delta N/N| \sim 0.05$ with scales of the order of 10 meters across and several kilometers along the magnetic field lines.

A nonlinear theory determining the conditions of existence and the structure of stationary striations has been recently developed (Gurevich et al 1995). The theory is in remarkably good agreement with the rocket observations (Kelley et al 1995, Franze nee Arce, et al. 1999).

During 1998 basing on a refined analysis of the rocket observational data (Franz nee Arce et al. 1999) Gurevich, Carlson and coworkers established a new physical phenomena -- self-focusing of a pump radiowave on a striations and the existence of a drift-type small scale oscillations of striations (Gurevich et al. 1999).

Another outstanding problem of ionospheric modiffication is Langmuir plasma turbulence and electron acceleration in the resonance layer near the reflection point of the heater wave.

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Professor Aleksander Gurevich

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

P. N. Lebedev Physical Institute
Leninsky pr.,53
Moscow 117924
Russia

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During 1999 Gurevich et al. theory of multiple acceleration was prolonged taking into account cavitation process, the width of acceleration layer and anomalous absorption of pump wave on striations. It allowed to compare in details the theory with Carlson et al. (1982) and Djuth et al. (1992) observations of suprathermal electrons by ISR method.

That confronts two most outstanding problems in this field: the excitation and nonlinear saturation of plasma wave turbulence and energization of electrons along with their relationship to excited optical emission. The objective of the project this year was theoretical investigation of these problems and comparison with experimental studies to quantitative test and after that refine the theory.

1.Observations

The most sensitive and direct ground based means of detecting the 10 - 20 eV suprathermal electrons is making incoherent scatter plasma line observations of the weak plasma waves produced in the ionosphere by these suprathermal electrons [Perkins and Salpeter, 1965]. Such technique has been used to study photo electron fluxes in the ionosphere [Yngvesson and Perkins, 1968].

Observations of fast suprathermal electrons in ionospheric modification experiments using incoherent scattering radar (ISR) technique were first proposed and realized by Carlson Wickwar and Mantas in 1972.

The powerful O-wave in resonance region near reflection point effectively excites plasma waves -— natural oscillations of ionospheric plasma. Plasma waves due to nonlinear cavitation process accelerate suprathermal electrons to the energies in excess of $\varepsilon \sim 10 \div 20$ eV, i.e. two orders of magnitude higher than the thermal electron energy $T_e \approx 0.1$ eV. The fast electrons propagate in the ionosphere at large distances $10 \div 100$ km from the acceleration region. Those electrons can excite nonthermal plasma waves, which could be detected by ISR.

Carlson et al. [1982] applied ISR technique to measure suprathermal electrons produced by high power HF radio waves over the Arecibo observatory. We present here two types of experimental data. The primary and secondary data were gathered on the nights 20 May 1972 and 13 July 1992 respectively. The primary data were published by Carlson et al. [1982], here we will revisit those results and supplement them with the original set of secondary data (Djuth et al. 1992).

On the night 20 May 1972 ionospheric modification was produced by transmitting P_0 =138$ kW of O-mode power at f = 7.63 MHz. Strong plasma waves were excited near the reflection point at the altitude z = 285 km. Night time plasma line intensities were observed to be enhanced by a factor 10 ÷ 100 extended to altitude below 250 km. When HF transmitter was turned off these enhanced plasma line intensities relaxed to their normal (near thermal) nighttime level in 1 ms. The HF transmitter was cycled 3 min on / 3 min off in order to isolate HF induced effects from natural background.

The 430 MHz incoherent scatter radar was used to diagnose the ionosphere, what gave a possibility to detect altitude profile of the background plasma temperature T_e and electron concentration N. The plasma line echo from suprathermal electrons provided the altitude of a set of plasma frequency f_p between 5 and 7.5 MHz. An altitude resolution was 1.5 km.

All data collected during this night was for Doppler downshifted plasma line only (due to equipment constrains) corresponding to upgoing plasma waves and consequently to upgoing suprathermal fluxes.

For a given diagnostic radar wavelength λ_r the main scattered signal comes from ionospheric plasma waves, whose wave vector is directed toward the radar, and the phase velocity v_{ph} is equal to the velocity of suprathermal electrons v

$$v_{ph} = (1/2)\ \lambda_r\ f_p \qquad (1)$$

Here f_p is local plasma frequency. For Arecibo radar λ_r = 70 cm and from eq. (1) one can obtain that the energy of electrons is

$$\varepsilon = (1/2)\ m v_{ph}^2 = 0.35\ f_p^2 \text{ eV} \qquad (2)$$

where $f_p = (e^2 N / 4\pi\ m)^{1/2}$ – Langmuir plasma frequency.

The intensities of plasma line echoes were shown in Fig.1 of Carlson et al. [1982] (see Supplement 1). They were expressed in terms of energy dependent '' temperature'' T_p [Yngvesson and Perkins, 1968]. A significant enhancement of radar echoes at large distance below the reflection point of the heating HF-wave at 285 km is apparent. The upgoing one-dimensional fluxes of suprathermal electrons at the heights 266 km and 256 km determined from these data are shown in Fig.2. (see Supplement 1.)

The secondary data were gathered (by Djuth et al.) at the night 13 July 1992. HF transmitter had 138 kW of O-mode power at 7.63 MHz. The reflection point was at the height 295 km, strong enhancement of plasma line was observed in the vicinity of reflection level.

In this experiment geometry the ISR beam crossed the disturbed region mapped along the magnetic lines at the heights 337 ÷ 367 km. The geometry of experiment and example of plasma line echoes collected at this region are shown in Fig.3 (see Supplement 1). The echoes were obtained both below and above the maximum of F-layer. Electron density $N_{max} \approx 5.5 \bullet 10^5$ cm^{-3} was reached at F-maximum heights z=350 km. Observed plasma line echoes correspond to upgoing electron flux. Here we emphasize a significant enhancement of plasma line echoes even at the heights more than 70 km above the reflection layer. The observations imply that the echoes could be seen even at altitudes higher than that, however the cut off comes from the geometry of the experiment.

2. Brief outline of the theory

In ionospheric modification experiments electrons gain the energy in a strongly disturbed Langmuir resonance layer near the reflection point of O - wave. In this layer plasma waves are effectively excited and then form density cavities (cavitons) due to nonlinear interactions. The last process was studied in details by a number of authors [see DuBois et al., 1993]. When crossing the cavitons and interacting with plasma waves fast electrons gain energy. In that way suprathermal tail of distribution function is growing up [see Wang et al, 1997].

The main idea of multiple acceleration theory is that fast electrons after leaving the acceleration layer and moving out of it can return back and gain some additional energy due to collisions with neutral molecules. The process could be repeated many times. Even electrons loose a fraction of their energy in the inelastic collisions outside of the acceleration layer, they gain energy again each time when rerun to the layer. That is why a wide region filled with strongly heated fast suprathermal electrons could be formed around the acceleration layer. This region is strongly elongated along the geomagnetic field. Its length can reach several hundred kilometers. A significant flux of suprathermal electrons moves to the magnetosphere, and can even reach the conjugated point. The theory shows that outside of the acceleration layer the properties of suprathermal electrons are fully determined by collisions with neutral molecules. The process is well studied, it depends on known parameters such as cross-sections of elastic and inelastic electron collisions with different components of the ionospheric plasma, and upon the height distribution of the ionospheric species. The acceleration process due to the multiple crossing of acceleration layer is averaged and in final form depends on two scalar factors only: full power density P absorbed by fast electrons in the acceleration layer, and characteristic parameter describing effectiveness of the acceleration inside the layer T_{ef}. They are related to concrete form of accelerating process, effective number of cavitons, their width, and so on. But outside of the acceleration layer only those two parameters fully describe the whole acceleration process.

Therefore distribution function of suprathermal electrons in the theory of multiple electron acceleration can be presented in a simple form

$$f_0(\varepsilon,z)= C\cdot K_0(\varepsilon/T_{ef})\cdot\exp\{- \left|\int_0^z (®z/[L_\varepsilon^\pm(z)\cdot\cos(\alpha)]\right|\} \qquad (3)$$

where K_0 is modified Bessel function, ε is the electron energy and T_{ef} is effective temperature of suprathermal electrons, while α is the angle between the vertical and geomagnetic field. Normalization constant C is directly connected with the power density P of the HF wave absorbed by the suprathermal electrons:

$$C = m^2 P / [4 \pi^3 T_{ef}^3 (\delta/3)^{1/2}] \qquad (4)$$

Here δ is an average fraction of electron energy lost in a single collision with neutral molecules.

According to eq. (3) the acceleration layer is assumed to be located at z=0 , while factor $L_\varepsilon^\pm(z)$ is the characteristic relaxation length of suprathermal electrons in upward (+) and downward directions (-)

$$L_\varepsilon^\pm(z) = [N_m^\pm \sigma_{tr}(\varepsilon)(3\delta)^{1/2}]^{-1} \qquad (5)$$

where $N_m^\pm = N_m^\pm (z)$ is the neutral density above (+) and below (-) the layer, $\sigma_{tr}(\varepsilon)$ is the total transport cross-section of electron - neutral collisions, and $\delta = \sigma_{in}/\sigma_{tr}$, where σ_{in} is the total cross-section of inelastic collisions, which includes ionization by electron impact. In σ_{tr} and σ_{in} the collisions with all neutral components N_{mk} are taken into account [Gurevich et al., 1985].

3. Comparison of the observations with theory

In the first experiment at 20 May 1972 upgoing in the radar ray direction fluxes of suprathermal electrons in the energy range $10\leq \varepsilon \leq 17$$ eV at the heights z_1 = 256 km and z_2 = 266 km were determined. The reflection point was at z_0 = 285 $ km. To compare it with the theory one has to determine the electron flux along radar direction $\mathbf{e_r}$:

$$J_r=(\mathbf{v},\mathbf{e_r})\mathbf{f}(\mathbf{v})$$

We introduce next upgoing and downgoing fluxes by integrating the flux J_r over corresponding angles in the velocity space. Taking into account that the angle between the geomagnetic field and vertical radar ray in Arecibo is $\alpha = 40^o$ we obtain the upgoing J_+ and downgoing J_- fluxes in energy interval $d\varepsilon$.

The result of calculations are presented in Fig.4 (see Supplement 1) for the given heights and different T_{ef}. It is apparent from the figure, that in the energy range $10 \leq \varepsilon \leq 20$ eV electron fluxes J reveal rather flat spectrum. Besides, there is no strong difference between the fluxes J at different temperatures T_{ef}.

On the other hand, the fluxes are effectively diminishing with the distance from the acceleration layer. It is apparent since the electron energy is lost in inelastic collisions with the neutral molecules. A fraction of those losses determines the optic emission from the disturbed region. One can deduce, that the main part of optic emission comes from the region of the order of 20 km around the acceleration layer. The relation between upgong and downgoing fluxes remains practically constant for all energies and depends on the angle α between radar ray direction and the geomagnetic field – for Arecibo at $\alpha = 40^o$ $J_+ / J_+ \approx 1.5$.

Comparison between the theory and observations presented in Fig.5 (see Supplement 1) shows a reasonable agreement between those two. In fact, behavior of flux spectrum at different heights is consistent with the theory for any of T_{ef} applied. Taking into account the absolute values of upgoing flux $J=(4\text{-}8) \times 10^5$ el/cm^{2}s$\cdot$eV at characteristic energies $10 \div 15$ eV obtained by Carlson et al 1982, one can find the absorbed power W_S of the HF wave converted into acceleration of the suprathermal electrons:

for $T_{ef} = 5$ eV $W_S \approx 5.6$ kW
for $T_{ef} = 7.5$ eV $W_S \approx 6.2$ kW
for $T_{ef} = 10$ eV $W_S \approx 8.5$ kW

In the calculations we took into account that according to Bernhard et al [1989] the heater beam at Arecibo had \$$7^o \times 14.3^o$ pattern. It gives an illuminated area at the reflection region $S \approx 1.95 \times 10^3$ km^2, thus the full absorbed power $W_S = P \cdot S$. Factor P was determined from the results presented in Fig.5 (see Supplement 1). It is apparent that the dependence of W_S on T_{ef} is not too strong. In the second experiment the height distribution of plasma line intensity was measured. In Fig.6 (Supplement 1) it is compared with the height dependence of the distribution function of suprathermal electrons $f_0(\varepsilon(z),z)$. Here energy $\varepsilon(z)$ is determined through the measured electron density distribution (Fig.3) by using eq. (2). One can see a sufficient agreement between the theory and observations. Note, that the normalized height dependence of the distribution function practically does not depend on the parameter T_{ef} (see Fig.6 in Supplement 1).

Therefore a reasonable agreement exists between the theory of multiple electron acceleration and the ISR observations in a wide region of the order of 100 km both below and above the reflection point of the powerful HF-wave.

4. Intensity of the Artificial Optical Emissions

The suprathermal electrons accelerated in the upper ionosphere due to the HF heating collide with the atoms and molecules exciting some lower electronic atomic levels. This in turn generates artificial emissions. So far, red- and green- line oxygen emissions have been observed corresponding to the electronic transitions O(1D) $\rightarrow$ O(3P) and O(1S) $\rightarrow$ O(3P).

The excitation rate of electronic levels of some ionospheric species by electron impact

$$k^{s}_{ex}=\int f(\varepsilon)\sigma^{s}_{ex}\ v\ d^{3}v$$

where σ^{s}_{ex} is th cross section for excitation of the s electron level by the electron impact. We follow suggestion of Mantas and Carlson [1991] made for σ^{s}_{ex} of the O(1D) electronic level that

$$\sigma^{s}_{ex} = \sigma_{0}(\varepsilon-\varepsilon_{th})\exp[-(\varepsilon-\varepsilon_{th})]$$

and extend it for other relevant cross sections.

The quenching factor has been considered

$$q=[1+t_{life}\ (k_q^{N2}N_{N2}+\ k_q^{O2}N_{O2}\ +\ k_q^{2}N_e)]^{-1}$$

Using distribution function of suprathermal electrons (3) -- (5) a complex of numerical calculations was fulfilled. It allows to determine:

1. Intensities of the red- and green-line of the oxygen atom induced by the suprathermal electrons in the F-region. They were compared with the observations of Bernhard et al. 1989, Haslett and Megill 1974, Newman et al. 1998, Gardner et al 1998

2. The effective temperature of suprathermal electrons which was evaluated from comparison of the theory with the observations of the artificial airglow is T_{ef} = 5 – 10 eV in agreement with ISR results.

5. Discussion and Conclusions

It was shown that the plasma line measurements by ISR method and optical emission observations are in an agreement with the theory of multiple electron acceleration. From the observational data and comparison them with the theory follows:

1. In ionospheric modification experiments a large number of suprathermal electrons in the energy range up to 20 eV is generated.

2. The suprathermal electrons are observed in a wide region of the order of 100 km both below and above the acceleration layer, centered near the reflection point of the HF heating wave.

3. Power $W_S \approx 5.6$-8.5 kW $\approx$ (4-6)% of the full transmitted heater power goes into the acceleration of suprathermal electrons. This energy is dissipated due to the generation of optical emissions, ionization and heating of ionized and neutral components of the ionospheric plasma. The characteristic dissipation length for suprathermal electrons depends strongly on the height, for z=250 km it is about 10 km, while for z ≈ 300$ km it is about 30 km.

4. The flux of suprathermal electrons into the magnetosphere depends strongly on the height z_0 of acceleration layer. For the studied cases z_0 = 285 km and z_0 = 295 km, and W_S = 8.5 kW, T_{ef} = 10 eV the flux into magnetosphere in the energy range 10 ÷ 20 eV is about 0.9 kW.

5. The obtained values of parameters T_{ef} and P give an opportunity to find some concrete features of the acceleration process, in particulary number density and characteristic width of cavitons.

We conclude, that plasma line observations combined with the theory and artificial optical emission observations enables us to obtain a significant information about the acceleration of the suprathermal electrons in ionospheric modification experiments. For the first time the structure and size of perturbed region filled with suprathermal electrons along with the full power going into the accelerated electrons is determined. We suggest that these experiments be repeated to obtain more information about the main features of acceleration, its dependence upon the reflection height and ionospheric conditions. Note that such observations were yet done in Arecibo only, though we expect that the latitude dependence of the effect could be very significant.

On the other hand the obtained agreement between the theory and observations make it possible to plan more detailed experiments. It will help to reach much better understanding of the physical mechanisms of electron acceleration and nonlinear processes in ionospheric plasma.

Parametric decay of upper hybrid waves trapped in striations and the structure of SEE downshifted maximum

In the frame of the present grant we analyze a parametric decay of upper hybrid plasma waves taking place inside density irregularities in the ionosphere - striations elongated along the magnetic field lines. Our prime concern is a process of decay of one UH wave $\omega_1,\mathbf{k_1}$ into another downshifted UH wave $\omega_2,\mathbf{k_2}$ and a low hybrid (LH) wave $\omega_L,\mathbf{k_L}$.

The parametric instability in inhomogeneous plasma may have either a character of a convective or an absolute instability.All of them have a character of the threshold phenomena. We investigate conditions when the instability becomes absolute since only this process may give rise to substantial effects.

The investigation gives a new understanding of the process of parametric decay of trapped inside striation waves and gives the possibility to estimate the width of down-shifted maximum.

The paper by A.Gurevich, H.Carlson, A.Lukyanov and K. Zybin “Parametric decay of upper hybrid waves trapped in striations and the structure of SEE downshifted maximum” in preparation.

New experiments are proposed to be performed in 2000 –- 2001 at HAARP facility by A.V. Gurevich with P.Cheung, T.Armstrong and with K.Groves and Yu.Yampolskij. A new laboratory experiment is proposed by A.Gurevich and P.Cheng (2000 – 2001).

6. Publications

1. A.V.Gurevich , H.C.Carlson, G.M.Milikh and K.P.Zybin "Suprathermal Electrons Generated in the Ionosphere Modified by Powerful Radio Waves" Geophys.Res.Lett (in preperetion)

2. A.V.Gurevich "Modern problems of Ionospheric Modifications" Radiofizika XLII, N7, 599 - 606, 1999

Two reports were presented at RF Ionospheric International Workshop, Santa Fe, New Mexico April 18-21, 1999. The reports are published in Workshop Proceeding V.I, p 16 - 34 and V.II, p 414 - 418

1. Invited review: A.V.Gurevich " HF Ionospheric Heating research – Russian view"

2. A.V.Gurevich, A.V.Lukyanov, K.P.Zybin and G.M.Milikh "Generation of the Suprathermal Electrons in the Ionosphere Caused by HF-Heating."

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SUPPLEMENT 1

Figure Captions

1. The dependance of T_p on height (a) and suprathermal electron energy (b).

2. Upgoing flux of suprathermal electrons versus their energy for the given heights.

3. The geomertry of the experiment (a) and observed plasma line spectra (b).

4. Upgoing flux of suprathermal electrons versus their energy computed for W_S =10 kW and for different values of T_{ef} and for given heights (4a, 4b).

5. Plasma line intensities computed for same T_{ef} as in Fig.4, the points with bars correspond to observations 1 ÷ 5 eV; 2 ÷ 7.5 eV; 3 ÷ 10 eV.

6. Plasma line spectra from Fig.3b compared with the theory.